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High performance apparel for protection

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Chapter 16 of *High-performance apparel*: *materials, developments and applications*
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Abstract: All animals have a protective covering of skin, generally supplemented by an additional layer of fur, scales, feathers or body armour. Consequently, we are surrounded by instructive models of protection – applicable to a great variety of environments and hazardous events. This chapter is particularly concerned with protection from injury resulting from impacts to the human body. The goal is the development of apparel (an additional layer designed for humans) that reduces risks of injury whilst maintaining usability and comfort for wearers. Understanding the mechanisms relevant to protection provides a starting-point for designing garments that absorb and diffuse the energies of impacts. However, a user-centred design approach must recognise that impact protection is just one of many factors to be considered during product development.

Keywords: Impact protection; protective materials; impact resistance; energy diffusion; product development.

1.0 Introduction

The world around us provides apparently innumerable examples of organisms displaying protective features. The diversity of mechanisms is noteworthy, and of particular interest for this chapter are different ways of protecting against impacts. Some vertebrates, like the tortoise and the armadillo, are equipped with a form of armour. However, the most widely used mechanisms utilise the skin. As any leather specialist will explain, skins and hides are complex structures and any generalisation has limitations. For the purposes of this chapter, the terminology used to describe skin identifies the epidermis, the grain and the corium.

The epidermis is of the order of 1% of the total thickness and made up of a protective layer of cells, normally removed in the leather manufacturing process. The grain layer is a composite material made up of collagen and elastin protein fibres. It is relatively tough with some extensibility. The corium is the inner layer and is a spongy, open-mesh structure made of collagen protein fibres. Although the corium is not as strong as the grain, it has superior elasticity and durability. The epidermis and grain layers have the property of spreading the effects of any impact over a larger area. The corium, because of its larger diameter fibres and looser intertwining, provides a cushioning function. The net effect is that the skin protects delicate body tissues and skeletal structures from damage during the normal processes of living. Additional protection to mammals may be provided by the skin’s fibrous surface covering (fur, hair, wool), but usually the main function of these coverings is insulation.

By analogy, garments designed for protection against impacts must have comparable functionality – a means of spreading the impacting forces and cushioning what lies beneath. Vertebrates do not have a rigid shape and physical activity can lead to large changes in body dimensions. Skin is remarkable for its extensibility and elastic recovery. These properties are taken for granted when we are considering what the human body can do when exercising, but they are more difficult to emulate in a garment. The challenge demands special skills from designers and product developers, so that the protective functionality is not lost because of body shape changes during movement. This is of particular importance with the protection of elbows and knees, for although it is relatively easy to protect a static limb, the design inputs required to avoid discomfort and inhibited movement are substantial.

Most research in this area has focussed on materials that provide the user with enhanced protection from impacts. Many of these take the form of polymeric sheets that need to be cut or moulded to shape before being incorporated into the garment. This means that garments are typically constructed with pockets carrying protective panels. Some other products use a textile substrate (for example, a knitted spacer fabric impregnated with a silicone material).

2.0 Impact resistant materials

Materials deform when they experience an applied force – whether it be a constant load or an impact. If the deformation is linear, where stress is proportional to strain, the material is described as elastic and Hooke's Law applies. When an applied force is removed from an elastic material, it returns to its original state. The energy associated with the compressional force is stored in the deformed material and released when the force is removed. Elastic materials do not absorb energy and effectively transmit impacts without any attenuation.

It is possible for a material to be elastic but not extensible. An example is the mineral quartz – it holds its shape, but behaves elastically and does not absorb energy. These properties make it suitable for applications in quartz watches, where the flow of a small electric current through the crystalline quartz makes it vibrate at an ultrasonic frequency. The vibrations are monitored and it has been determined that 32,768 vibrations occur every second. Since quartz is elastic, the vibrator does not absorb energy, the current drawn from the battery is very low, and the watch keeps good time.

Many materials are not elastic and energy is absorbed during extension and contraction. Such materials usually behave elastically with small extensions, and then experience permanent deformations with higher extensions. They are described as visco-elastic and are able to provide additional protection from impacts. A key property of visco-elastic polymers (e.g. textile fibres) is that they respond to tension by undergoing both plastic and elastic deformation. Plastic deformation is structural, involving shearing, creep, and molecular rearrangement. The energy required to achieve this deformation is absorbed by the material and dispersed as heat.

As an example of a visco-elastic material, consider skin tissue. It experiences deformation when it is pinched using a finger and thumb. When the deformation is small, the skin behaves elastically, recovering from the pinch as quickly as the skin is released. When the deformation becomes more significant, the skin takes more time to return to its original position. Not all skin behaves the same: the skin of a young child is more elastic than that of a parent.

Rubber is a natural visco-elastic material that is normally used when the application requires elasticity. A synthetic rubber is called an elastomer. Both rubber and elastomers can be engineered to achieve desirable products: whether it be high elasticity, high energy absorption, heat resistance, chemical resistance, etc. If the goal is to enhance absorption, the binding forces between polymers are engineered so that the deformation breaks the intermolecular bonds leading to the absorption of energy.

Some visco-elastic materials exhibit changes in viscosity during deformation. When the viscosity of a liquid increases with increasing shear rate, it is described as a dilatant fluid. If incorporated into a polymeric substrate, the assemblage is known as a dilatant material. This is relevant to impact protection, because an incident blow causes initial rapid shearing accompanied by stiffening. The affected area spreads the load over a wider area and this reduces the peak forces experienced. After the impact, the material reverts to its normal state of flexibility.

2.1 Industrial materials

A range of impact-resistant materials have been produced for performance apparel: for sportswear, outdoor clothing, and industrial protection. These include the following.

D3O is a polymer-based dilatant material produced either as a pliable sheet, or as shaped parts for inclusion in a garment. When experiencing an impact, the material locally stiffens to distribute the applied forces and then returns to its normal state. The energy of the impact is dissipated within the visco-elastic foam. A variety of base materials are offered, with different selection criteria.

Poron XRD is an open-cell urethane foam that has dilatant properties when impacted quickly. It is available in sheet form, cut by the user to incorporate in performance products. The energy of the impact is dissipated within the visco-elastic foam. A variety of base materials are offered, with different selection criteria.

The DEFLEXION S-range is a knitted polyester spacer fabric impregnated with silicone, and the DEFLEXION TP-range is a sheet dilatant material. The S range has an open breathable structure which is highly flexible. The TP range has a solid sheet appearance, and breathability is imparted by holes punched through the sheet. These products are cut to shape by the user and either sewn into the garment or inserted into specially made pockets. DEFLEXION™ technology was produced and marketed by Dow Corning, but the products are now withdrawn.

Sorbothane® is described as a thermoset, polyether-based, polyurethane material. It may be helpful to think of this material as a synthetic rubber: initially a liquid but transformed chemically to acquire a very high viscosity with properties analogous to a solid. Sorbothane® has excellent shock and vibration absorbing characteristics and has a variety of uses in industrial applications and in high-performance apparel (particularly footwear insoles)

EVA foams are widely used for protection as a lower cost alternative to the above products. The material is ethyl vinyl acetate, and can have a variety of formulations to create foams with differing properties of protection.

3.0 Comparisons between materials

A range of impact-resistant materials were obtained for comparative evaluation. These included some of the branded materials described above along with leather (as a natural benchmarking material) and a polyvinylnitrile thermoset polymer.

Material	Notes
D3O	Dilatant material
Deflexion S-range	Polyester spacer fabric with silicone
Deflexion TP-range	Dilatant material
EVA foam	Ethyl vinyl acetate foam
Leather	Natural benchmarking material
Poron XRD	Dilatant open-cell urethane foam
PVN	Polyvinylnitrile thermoset polymer

These materials were obtained in different thicknesses, ranging from 2mm to over 15 mm.

3.1 Experimental method

There are numerous testing scenarios for determining impact resistance. Of these, two standard methods were considered of greatest relevance to apparel-related work. These are: *Industrial bump caps* (BS EN 812:1997/A1, 2001) and *Specification for head protectors for cricketers* (BS 7928, 1998). Both involve a striker falling on a surface, with the protective product experiencing the impact. The data gathered relates to material properties affecting peak forces and impact durations. The experimental equipment detects the forces experienced by a transducer attached to an anvil located under the protective material. A similar method is specified by the International Rugby Board. Their hammer and anvil test involves a flat striking surface (weighing 5kg) falling on to a protective pad which rests on a steel anvil (Pain et al. 2008).

The purpose-built impact attenuation equipment used for this research has a striker, a steel ball, falling on to a flat anvil on which the protective material is placed. The pressure sensors are located below the sample material and the forces transmitted through the material by the impactor are recorded in the form of a load-versus-time data set. By varying the diameter of the ball, different impact profiles can be created. The mass and height of fall parameters determine the impact energy. For research purposes, impacts of 5, 10 and 15 joules are used. An illustration of the test equipment is shown in Figure 1.

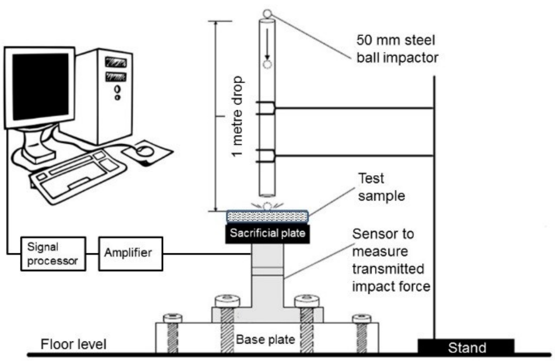

Figure 1. Impact attenuation test rig

Impact forces are experienced by the test material, and the forces reaching the support plate are recorded using a load washer. A typical data set is plotted in Figure 2. With some samples, the ball bounces a few times before coming to rest, but in other cases, often with thicker materials, there is no bounce. From traces like this, the durations of impacts on different thicknesses of materials can be measured.

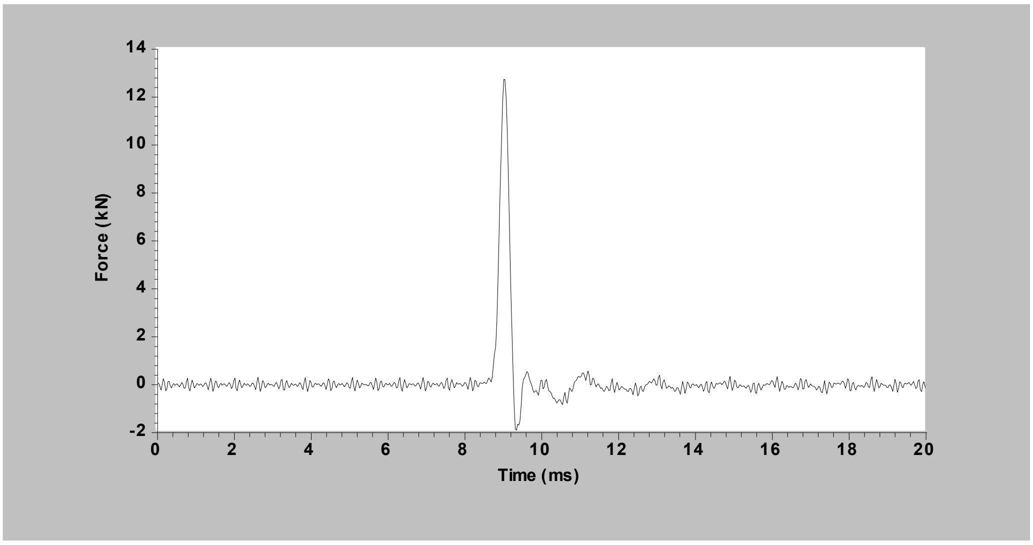

Figure 2. Impact forces experienced with protection provided by 3 mm Poron XRD.

The experimental results reported here give the mean obtained from 5 measurements, with standard deviations being, typically, less than 5% of the means.

3.2 Results

A selection of commercial materials was tested to compare their abilities to protect against impact. In addition, unfinished leather was tested to provide benchmark values. The rationale is that leather has been used in garments to provide wearers with enhanced protection. Figure 3 presents peak force variations for a range of materials with different thicknesses. Thinner materials experienced higher peak forces. As thicknesses increase, the commercial products designed to cushion impacts reduced peak forces more effectively than the leather sample.

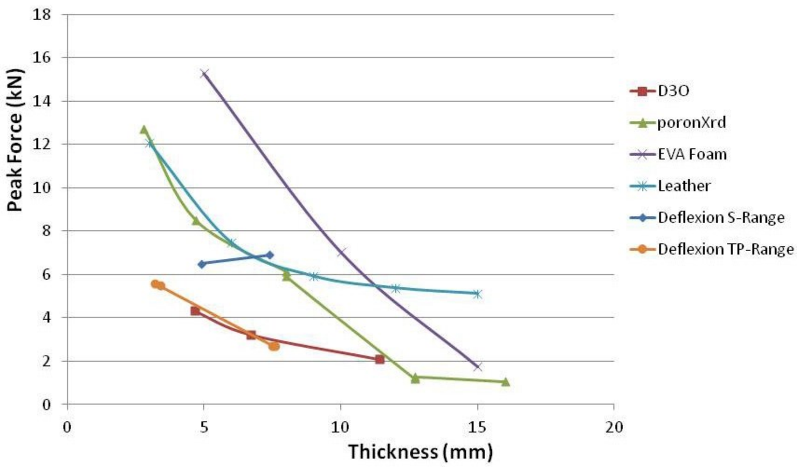

Figure 3. Findings from Impact Attenuation Tests

The EVA foam samples were taken from commercial garments designed for rugby players. Neither the 5 mm (used for arm protection) nor the 10 mm (used for shoulder protection) sample compared favourably with leather. The maximum thickness for shoulder protection permitted by the International Rugby Board is 10 mm. In general, the branded commercial materials performed better than leather, although clear differences between them are apparent below thicknesses of 5 mm. Above peak forces of 12 kN, damage was caused by the impacting sphere, resulting in a hole through the material.

Whilst energy absorption by the protective material must be a factor, other mechanisms have been identified during this research. Figure 4 presents data plots for 5 Joule impacts on different thicknesses of PORON XRD. The vertical axis records the measured force in kN, and the horizontal axis records time in tenths of a millisecond. The impact durations are in the range 2 ms to 10 ms.

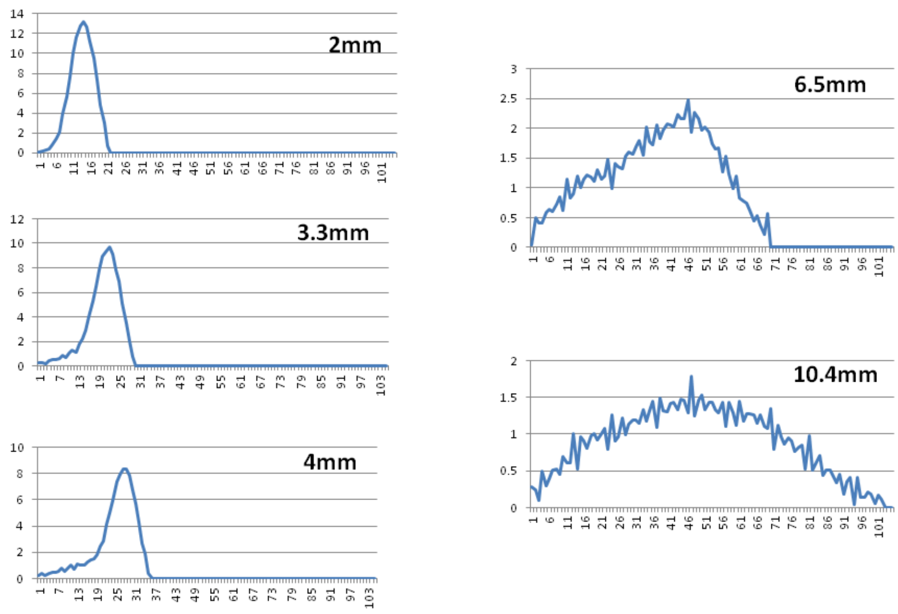

Figure 4. Variation of impact duration with thickness of material (Poron XRD)

These test results show a broadening of the impact force traces resulting from the increasing thickness of a protective material. If energy absorption were the dominant factor, it is expected that the peak forces would reduce with relatively little change in the impact timescale. On the other hand, when the impacting event is experienced over a longer timescale, the material acts as a cushion and, as a consequence, the peak forces must reduce.

A third mechanism for reducing peak forces is to increase the area of material affected by the impact. When a larger area experiences an impacting force, the energy of the impact is more widely distributed and the peak force at any particular location is reduced. As energy is dissipated within the protective material, the test equipment should also record a reduction in the measured forces.

By contrast, body armour for withstanding ballistic impacts require substantial energy absorption in order to protect the wearer. Joo and Kang (2008) have analysed nine different mechanisms actively contributing to protection against ballistic impacts. They found that kinetic energy loss by inelastic collision was dominant. Yang & Chen (2017) have modelled energy absorption for individual layers of a ballistic armour panel and have demonstrated efficiencies of 30%–60%.

One commercial product that sets out to distribute the energy of a non-ballistic impact over a larger area is isoBLOX^{TM}. This polymeric sheet is about 1mm thick and the manufacturers claim that their product operates by promoting both energy absorption and energy dispersion. Experimental work was undertaken to assess the influence of isoBLOX^{TM} used alongside PVN sheets of different thickness. Peak forces were measured and plotted in Figure 5.

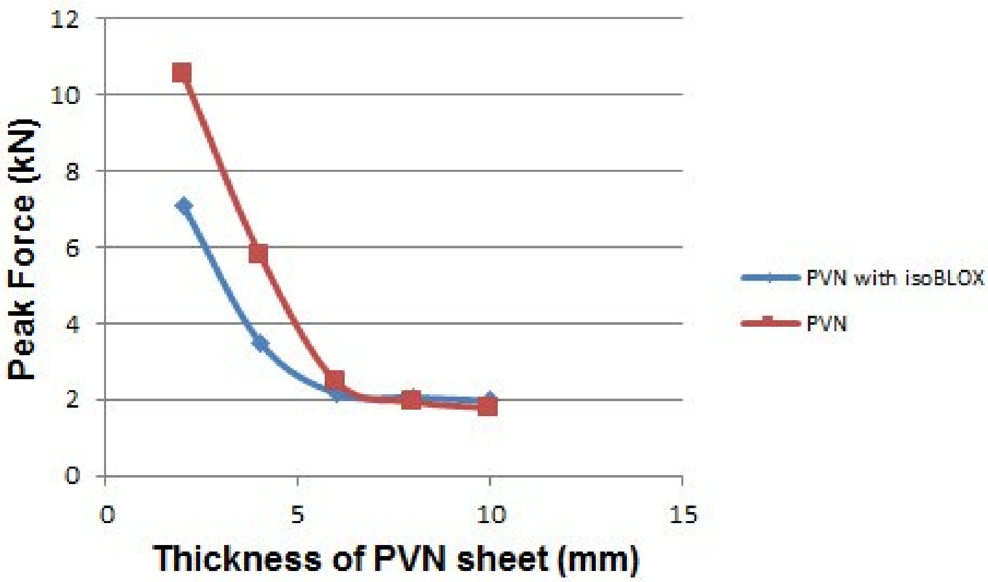

Figure 5. Experimental results obtained with isoBLOX^{TM}

The PVN material provides effective protection above 6mm thickness, and the addition of an isoBLOX^{TM} sheet makes little difference to the performance under these experimental conditions. However, there are distinct differences for the thinner layers of PVN. However, it should be noticed that if the isoBLOX^{TM} curve is shifted to reflect the 1mm thickness of the material, the two curves almost overlap.

3.3 Discussion

Designers ~~would~~ like to work with thin, flexible materials suitable for imparting impact protection to apparel. Energy absorption is relevant to vibration reduction, but it has not emerged as a major factor for thin materials. From the research noted above, the most important parameter appears to the ability of the material to extend the impact time so that the energy of the impact can be dissipated with less trauma. The parameter that stands out as associated with this dissipation is thickness. There are remaining questions about increasing the area of impact, so that a greater volume of energy-absorbing material can be involved. This would appear to be the relevance of dilatant materials, so that the impact is met by a stiffer surface that transmits the energy to a greater volume of the protective material.

Thus, there are three parameters of interest:

- The impact time, with longer times distributing the incident forces over an extended time interval, thereby reducing shock and peak forces;
- Energy absorption, with materials that are viscous rather than elastic;
- The area of impact, with larger areas allowing the forces to be spread and local peak forces reduced.

What does emerge from the empirical work noted above is that materials of less than 5mm have limited potential for protection. Market-leading products perform better than natural leather of the same thickness, but the improvements are marginal. Furthermore, 5mm thickness would still be regarded as bulky for many performance garments, so the quest for improved approaches for impact protection continues.

The ongoing challenges of finding thin, flexible and effective materials to enhance protection against impacts brings us back to consider the lessons that can be learned from skin and other natural materials that deliver protection to humans and animals. This approach has become mainstream in recent years in the science of biomimetics. Some examples are as follows.

- Mussels receive mechanical impacts are a result of wave action, particularly during storms. These animals use byssus threads to attach to rocks and this works remarkably well. Researchers (Qin & Buehler, 2013) report that the dynamical forces far exceed the measured strength of byssus threads and their attachment to the environment. It emerges that a combination of rigid and elastic materials enables mussels to dissipate the impact energy. The key is to have 80% rigid and 20% elastic components organised within the structure of the byssus threads.

- Woodpecker drumming occurs at a rate of about 20 impacts per second, with decelerations of 1200 g, and the drumming sessions may be repeated 500-600 times per day. By contrast, humans can lose consciousness when experiencing decelerations of 4-6 g and are left concussed with a single deceleration of about 100 g. Researchers (Yoon & Park, 2011) have identified a set of complementary strategies to withstand these extreme impacts. The relevant head structures are the beak (hard but elastic), the hyoid (a sinewy, springy tongue-supporting structure that extends behind the skull), spongy bone (located in a strategic part of the skull), and skull bone with cerebrospinal fluid (engineered to interact to suppress vibration). Stimulated by these observations, the researchers constructed "a new shock-absorbing system is designed to protect commercial micromachined devices from unwanted high-g and high-frequency mechanical excitations."

- A mollusc, known as the scaly-foot gastropod, was discovered living in the deep sea near the Kairei Indian hydrothermal vent field on the Central Indian Ridge. The natural environment for the animal is harsh. There are extremes of temperatures, high pressures and high acidity levels that can easily damage shells of calcium carbonate. Brachyuran crabs live in the vicinity and these "are known to compress gastropod mollusc shells between their chela" with loads of up to 60N. Without shells that can withstand the crabs and the acidity, these molluscs wold not survive long. The shells were found to have three highly organised layers as follows.
  The outer layer is mineralised, containing iron sulphide particles (derived from hydrothermal fluids). The middle layer is the periostracum (the template for shell mineralization, providing protection against corrosive and dissolutive marine

environments, and also chemical protection from boring organisms). The inner layer has a layered structure of conventional aragonite. As the researchers (Yao et al., 2010) explained: "We have determined through nanoscale experiments and computational simulations of a predatory attack that the specific combination of different materials, microstructures, interfacial geometries, gradation, and layering are advantageous for penetration resistance, energy dissipation, mitigation of fracture and crack arrest, reduction of back deflections, and resistance to bending and tensile loads."

- Australian researchers have identified desirable properties exhibited by the human tissue periosteum. This material envelops bony surfaces to enhance the strength of the skeleton. Using a 3D imaging system, they mapped the micro-structure of this tissue to find that, like skin, it is composed of a particular mix of specialised collagen and elastin fibres. The challenge then was to create a biomimetic fabric that possessed similar properties. The researchers found they could use jacquard weaving technology to mimic the micro-structure, but at a much coarser scale than observed in human tissue. The collagen fibres were represented by filaments of silk, and the elastin fibres by elastane fibres. The resultant textile swatches were found to have stress-strain properties similar to periosteum, a finding which then led to publication (Ng et al. 2017).

In all these examples, there is no one "magic" material that can provide complete solutions for impact challenges. A combination of mechanisms with materials of different properties can lead to engineered solutions that are more effective.

4.0 R&D initiatives for enhanced protection

4.1 Test methods

The test standards *Industrial bump caps* (BS EN 812: 1998) and *Specification for head protectors for cricketers* (BS 7928, 1998) have already been mentioned. The first of these standards was updated in 2012 and the second in 2013. The updates did not affect the principles of impact testing. Both make use of a striker impacting a target to enable measurements of forces experienced by the target. The bump cap test results in an impact energy of nominally 12.5 J and the cricketer head protector test has an impact of nominally 15.0 J. The principle of drop-weight testing can be adapted to the materials and application areas of interest. For example, Liu et al. (2012) made use of a striker of weight 6.5 kg with a flat face of 150 mm diameter. This was released to drop onto an anvil made of polished steel with a circular face of the same dimensions. The test conditions gave an impact energy of 12.74 J and an impact speed of 1.98 m/s. The transmitted force was measured by a load cell, and the acceleration/deceleration of the drop striker was measured using an accelerometer fixed to the striker.

Some commercially available materials have been tested by their manufacturers using ASTM F1976: 06. This has the title: *Standard Test Method for Impact Attenuation Properties of Athletic Shoes Using an Impact Test.* The principle is to strike the sole of the footwear with a moderate impact of 5 joules or a high impact of 7 joules and measure the peak forces experienced. ASTM F1614 specifies three ways of assessing heel forces experienced wearing athletic shoes: (A) the falling weight impact test, (B) the compression force controlled machine and (C) the compression displacement controlled machine. Schwanitz et al. (2010) used Test methods A and B alongside a hydraulic impact test of their own to compare the test procedures on five commercial brands of running shoe. Their conclusions are cautionary because mechanical energy was "absorbed by the same shoe in a different manner dependent on the used test procedure."

A technique using plastilina modelling clay has been used for body armour ballistic testing as described in the NIJ Standard: 0101.04 (2000). Projectiles are fired into, or dropped onto, the clay and the indentations measured using a contour gauge. Drop test experiments may also allow the recording of depression diameters. This method has been adapted for the testing of sportswear by Nayak et al. (2017) and four fabric samples were compared for their ability to provide impact protection. It should be noted that the quality of results for this approach to testing has been extensively researched and the findings have been documented (National Research Council, 2012).

4.2 Spacer fabrics

Spacer fabrics are considered by many to be ideal for cushioning applications. They are often warp knitted, have a face layer, a back layer and an internal spacer layer. The spacer yarns are typically monofilaments that connect the two outer layers to form a three-dimensional structure. They are already used in applications such as car seat padding, for vibration reduction, and as breathable panels in apparel.

Twelve sample spacer fabrics were prepared by Liu et al. (2012), with thicknesses ranging from 5.64 mm to 10.62 mm. The spacer layer was knitted with polyester monofilament of 0.2 mm diameter for eleven of the samples and 0.16 mm diameter for the twelfth. They found that filament coarseness is a significant variable, with coarser monofilaments providing more protection. The spacer yarn inclination was found to significantly affect impact behaviour. An optimum structure is needed: not too vertical, nor too inclined. Comparisons between spacer fabrics and other protective materials were not obtained. Subsequent research (Liu et al. 2014a, 2014b) involved a hemispherical test surface and impact energies up to 50 J. This revealed greater complexity in understanding both impacts and the effectiveness of spacer fabric as a protective material.

Chen et al. (2017) analysed the compressive deformation mechanism of a spacer filament with the objective of providing guidance for designers of spacer fabrics. They divided the compression process into four stages: the Stiff Stage, the Elastic Stage, the Restful Stage, and the Ineffective Stage.

Zhao et al. (2017) have focussed attention on weft knitted spacer fabrics because of the potential for seamless shaping of impact protectors. Sixteen samples of weft-knitted spacer fabrics were knitted with varying spacer yarn patterns, filament diameters and fabric densities. Thicknesses ranged from 2.7 mm to 6.4 mm. Their work is concerned with cushioning rather than dynamic impact protection, but the approach is one that has great potential for producing shaped panels for protection.

Nayak et al (2017) considered the potential of using spacer fabrics as alternatives to foam padding. Three samples were knitted. Fabric A had mercerized cotton and Elastane for external layers, with ballistic nylon as the internal layer. Fabrics B and C both had Dyneema and Elastane external layers and a Dyneema internal layer, but knitted with different structures. These were compared with a closed cell foam obtained from a rugby clothing manufacturer. Their conclusion: "the flexible 3D knitted textile structures can provide equivalent level of impact protection achieved by the commercial foam used in the rugby clothing. The flexible knitted structures can also provide higher level of comfort to the players compared to the commercial foam as indicated by higher air permeability and lower thermal resistance and water vapour resistance."

The research into spacer fabrics raises expectations that impact protection is feasible using these materials. The papers also show that suitable properties need to be engineered during the design process. Spacer fabrics designed to permit permeability and cushioning may provide little protection, as experiments with commodity spacer fabrics undertaken by the writer have demonstrated. There is also scope for composite materials, and reference has already been made to the Deflexion S-range: polyester spacer fabrics impregnated with a silicone covering resulting in permeable, flexible protective materials. Zhou et al. (2013) has also developed this approach by making use of micro-gels.

4.3 Auxetic materials

The key characteristic of an auxetic material is that it expands in the lateral direction when stretched longitudinally. Most materials thin laterally when stretched, but an auxetic material will extend itself laterally when pulled. Technically, this behaviour is described as the material having a negative Poisson's ratio (the ratio describing the contraction in the transverse direction to the longitudinal extension along the direction of stretching). It may be useful to associate auxetic materials with biomimetics, as Alderson & Alderson (2007, 566) explain: "biological materials have also been found to be auxetic and these include certain forms of skin (e.g. cat skin, salamander skin, and cow teat skin) and load-bearing cancellous bone from human shins".

Alderson & Alderson (2007) point out that in 2001, auxetic fibres were fabricated using a partial melt spinning technique. Subsequently, polypropylene, polyester , and nylon fibres have been produced with auxetic properties. A major problem for the textile sector is that commercial spinning machinery does not handle auxetic fibres well, so nonwoven fabrics have been produced rather than yarns and woven/knitted fabrics. There has been more interest in auxetic structures made from conventional yarns. Research in this area is reported by Wright et al. (2012).

A review of textile-related research and discussion of potential applications is by Wang & Hu (2014). Of particular interest here is the enhanced indentation resistance reported for auxetic materials. With an impact on a conventional substrate, the material thins under the impact point. With an auxetic substrate, the material expands beneath the impactor. In the case of one particular polyethelyne foam, the auxetic version was found to give 2.5 times the indentation resistance of the conventional material. Another parameter of interest is energy absorption. Tests on foams show superior performance here compared to conventional foams. Regarding the potential for protective clothing, Wang & Hu (2014, 1607-8) have this to say:
"Auxetic fabrics can be used in protective clothing and equipment because of their good energy absorption properties and shape fitting. Protective clothing and equipment are indispensable for some dangerous sports, such as riding, racing and skating, to protect wearers from injuries by impact forces. In particular, the parts of the body, such as elbows and knees, which are easily injured, need to be protected, so that the protective pads are usually used in these areas of the protective clothing and equipment. However, the protective pads found on today's market are mostly made from foams that have low air permeability.

Three dimensional auxetic fabrics (e.g. auxetic spacer fabrics) can be used to replace foams with ones that have a better comfort property."

The technical issues facing product developers interested in the potential of auxetics are many. The research base is also underdeveloped. However, this is an area, along with spacer fabrics, where there are potentially significant rewards.

5.0 Design issues for protective apparel (refer to Chapter 9)

5.1 Design principles.

Protective apparel products require various performance characteristics such as durability, comfort, identity and recognition, and functionality. However, these are dependent on the type of application, level of physical activity, environmental context, age of user and other special functions (El Mogahzy 2008). A User-Centred Design Approach has the potential of identifying and addressing the diverse issues relating to specific products. This section draws attention to various cases illustrative of the principles and the challenges. See also Black et al. (2005) and Chapter 9 of this volume.

5.2 Case: Protection for Rugby players (Tyler & Venkatraman, 2012)

In the context of rugby, with particular focus on protection from impact using pads or materials, six factors were selected for attention. These are: mechanism of injury, flexibility, bulkiness, breathability, thickness and ability to attach these pads on to the clothing. User feedback found that bulky inserts are not well received as they restrict free movement as well as offer poor comfort. Designing functional protective gear for sports is challenging and demanding since protection is sometimes achieved at the expense of comfort (thick pads, stiff, heavy and multi-layered, non-breathable). These factors relevant to designing and developing functional garments are presented in Figure 6.

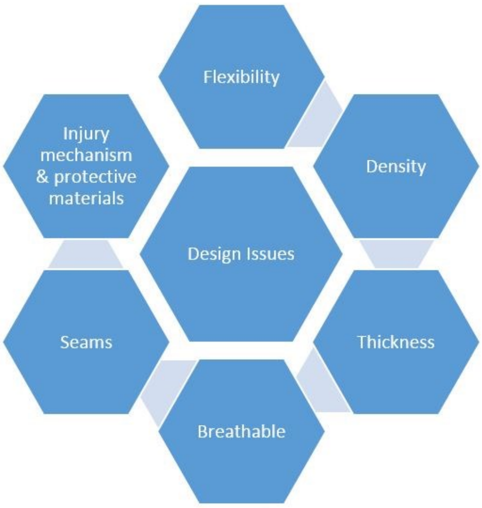

Figure 6 Factors influencing the design of garments with impact protection

Rugby is a high intensive team sport and players move fast in the field. The sport is popular among men; however women are getting more involved, particularly in college/school levels. 40% of reported injuries are muscular strains or contusions, 30% are sprains, followed by dislocations, fractures, lacerations and overuse injuries. Players wear protective clothing in the form of head gear, padded vests, shorts, shin guards, mouth guards and support sleeves to reduce the risk of sprains and cramps. World Rugby has specified the circumstances in which padding can be introduced to the clothing of players, with restrictions on the dimensions of the protective materials (World Rugby, 2017)

The following issues express user and developer concerns about garment design and development to incorporate protection. Generally most protective pads or foams are available in thicknesses above 5 mm and it becomes a challenge to incorporate it in the garment.

- Pads for shoulders and sleeves lack any moulding of the shape. Pads used in some samples are large and garments do not fit well on the body when pads tend to hold the fabric out.
- Pads used in some products were smaller (shoulder region) which offered less protection to the wearer.
- Seams used in these garments were often overlocked, affecting wearer comfort. Some products had body panels sewn together with flatlock seams to enhance comfort. Other products had pads that were sandwiched between fabrics in form of pouches.
- Thicker foams or pads have perforations to allow flexibility and moisture transport. However in other areas, the pads block air/moisture movement allowing low breathability hence poor comfort.
- Pads were stiffer and reduced the flexibility to conform to various contour of the shoulder region. Unlike heavy and bulky shoulder pads used for American Baseball, the pads used for Rugby vests required flexibility

An epidemiological study by Crichton et al. (2012) investigated videos of 24 elite rugby players sustaining injury and reported that there were three common injury mechanisms in rugby resulting in serious shoulder injuries – 'Try Scorer', 'Direct Impact' and 'Tackler'. It is necessary to understand the nature of the injury and design shoulder padding mechanisms which provide maximum protection to these common injury patterns.

- Try scorer – out stretched arm when scoring a try.
- Direct impact - direct blow to the arm or shoulder when held by the side in neutral or slight adduction (moving of a body part toward the central axis of the body).
- Tackler – it involves a levering force on the glenohumeral joint due to movement of the outstretched arm.

Knowledge of the mechanisms involved in rugby shoulder injury is useful in understanding the pathological injuries and aiding the development of injury prevention methods such as padded vests.

Users recognise that a typical shoulder padded vest does not provide complete coverage to the shoulder region. The shoulder pads should be flexible to cover the vulnerable regions: sternoclavicular joint, acromioclavicular, and Glenohumeral joint (Crichton et al., 2012). Many of the commercial padded vests did not provide protection to these regions satisfactorily. Pain et al. (2008) reported that, when tackled using a shoulder pad, the reduction in force was noticed only in the acromioclavicular joint while forces in other areas of the shoulder region were not reduced. In other words, the shoulder experienced considerable impact during tackling, but the protection provided was partial in scope.

5.3 Case: Protection for motorcyclists

For many years, motorcyclist clothing has been marketed and purchased as fashion items that have some ability to protect against wind, rain, heat and cold. It has been important for riders to "look good" in all seasons, and leather emerged as the material of choice. However, the increasing trend of injuries has made it clear that motorcyclist clothing must also be designed to improve safety. Initially, the emphasis was on helmets, and regulation is now well established. Whilst leather has many beneficial properties, not all leathers are robust enough to provide protection in a crash. Varnsverry (2005) lists seven material characteristics that were required by the sport's governing body, the FIM (Fédération Internationale de Motocyclisme):

- fire retardant
- resistant to abrasion
- low coefficient of friction against all types of asphalt
- perspiration-absorbing qualities
- medical test - non-toxic and non-allergenic
- of a quality that does not melt
- non-flammable.

Formal standards were introduced in Europe: BS EN 13595:2002. This was met with mixed reactions from users, who were not always appreciative of regulation about what they should wear. Varnsferry (2005, 719) comments: "The European riders' groups initial display of a healthy ambivalence towards the standards was also due to concerns that the documents might pave the way for compulsory protective clothing for motorcyclists; however, this was tempered by their broad support for some form of independent and recognisable mark of fitness for purpose which would enable consumers to differentiate between competing products in the marketplace."

An assessment of the capabilities of motorcycle protective clothing to reduce risks of injury in crashes was undertaken by de Rome et al. (2011). Subjects were either riders or passengers involved in motorcycle crashes on Australian roads. A correlation was found between wearing protective clothing and the extent of crash injuries, and the researchers were confident that protective clothing is a justifiable safety issue. However, they also found evidence that not all the products being marketed to motorcyclists are fit for purpose. Statistics were obtained for gloves (25.7%), jackets (29.7%) and pants (28.1%), all of which were assessed to have failed due to material damage in the crash. They write: "The proportion of clothing items that failed under crash conditions indicates a need for improved quality control" (p.1893).

5.4 Hip Protectors

Well over a million elderly people per year experience a hip fracture resulting from a fall. Hip fractures are said to be the main reason for people entering nursing homes. Early feedback on their use gave positive results, and hip protectors were recommended by many professionals. However, a systematic review of trials undertaken by Parker et al. (2006) failed to confirm that they were having a beneficial effect. Their abstract concludes: "No evidence was found of any significant effect of hip protectors on incidence of pelvic or other fractures. No important adverse effects of hip protectors were reported, but compliance, particularly in the long term, was poor. On the basis of early reports of randomised trials, hip protectors were advocated. Accumulating evidence indicates that hip protectors are an ineffective intervention for those living at home and that their effectiveness in an institutional setting is uncertain."

Experimental work with 26 commercially available hip protectors was undertaken by Liang et al. (2011). A mechanical test system (simulating sideways falls) measured the attenuation in femoral neck force generated by an impactor striking at three impact velocities. This revealed that the protectors utilised a diversity of designs and, depending on the initial conditions, the protectors exhibited a diversity of protective characteristics. The authors anticipated that their work would assist the interpretation of results obtained in previous clinical trials.

Clearly, there is a case for a much more structured approach to the design of hip protectors, so that they can be tested objectively and provide a stated level of protection.

Incidentally, one of these protectors has relevance to the section on spacer fabrics (above). Tytex A/S has developed a hip protector SAFEHIP® by laminating two thin and soft weft-knitted spacer fabrics to be the cover layers for two thick and rigid warp-knitted spacer fabrics. The goal is to combine comfort with energy absorption and the product's horseshoe shape aims to provide the user with additional benefits.

6.0 Future trends

Functional garments have not only stimulated product development for numerous sectors (sportswear, medical, industrial, public services and military) but also R&D by manufacturers, brand owners and universities. There is much activity in the development of new materials, new processes and new technologies.

This chapter has considered the trend towards lighter weight and flexible materials that can enhance impact protection, which can be used in the context of holistic design of functional products. The design process must consider impact protection as just one factor in the development of commercial products. To handle the broader design issues, design managers need to ensure that the full range of skills are available to ensure robust decisions and avoid extensive reworking of the product specification. For elaboration of this challenge, refer to Tyler (2008, Chapter 9).

This chapter has drawn attention to the challenge of developing thin, flexible protective materials and to the potential for biomimetic-influenced research into composite materials. Whatever the source of inspiration, the quest for improved protective materials will continue.

The three case studies illustrative of design principles demonstrate that there is much groundwork to be done to develop the knowledge base needed to successfully develop functional products. Regarding the rugby shirts, commercial products were found to have pads that appeared imposed on the garment, undermining the visual appearance and comfort in use. Also, the location of the pads did not correspond well with identified needs. Regarding motorcyclists' protection, there are indicators that many commercial products are not fit for purpose. In the case of hip protectors, the necessary groundwork has not been done, and products are appearing on the market which make claims but are short on evidence. The general point is that developers of functional clothing must properly research their product, their target users, and develop the evidence base to support their claims.

Longer term, the most significant trend is likely to be the incorporation of microelectronic devices to monitor the impacts experienced by users. A priority would appear to be with headwear, where a micro-accelerometer can be embedded in the head protector to inform the coach and medical attendant about a collision and the implications for concussion.

Sportswear is already seeing this trend, with sensors providing feedback of physiological information to trainers or the wearers.

7.0 Sources of further information and advice

- Sorbothane http://www. sorbothane.co.uk/ http://www.sorbothane.com
- D3O http://www.d3o.com/
- Deflexion™ This product is no longer offered by Dow Corning.
- Isoblox™ http://isoblox.com/
- Xrd® and PoronXrd http://www.xrd.tech/index.aspx
- Tytex SAFEHIP® http://tytex.com/products/hip-protection

8.0 References

Alderson, A. & Alderson, K.L. (2007) Auxetic materials, *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 2007, 221(4), 565-575.

Black, S., Kapsali, V., Bougourd, J. and Geesin, F. (2005) Fashion and function - factors affecting the design and use of protective clothing. In: Scott, R.A. (ed.) *Textiles for protection*. Cambridge: Woodhead Publishing Limited, 60-89.

BS EN 812 (1998, 2012). *Industrial bump caps,* British Standards Institution.

BS 7928 (1998, 2013). *Specification for head protectors for cricketers*, British Standards Institution.

BS EN 13595 (2002). *Protective clothing for professional motorcycle riders. Jackets, trousers and one piece or divided suits, Parts 1-4*. British Standards Institution.

Chen, M-y., Lai, K., Sun, R-j., Zhao, W-z. & Chen, X. (2017) Compressive deformation and load of a spacer filament in a warp-knitted spacer fabric. *Textile Research Journal*, 87(5), 631–640.

Crichton, J., Jones, D., & Funk, L. (2012) Mechanisms of shoulder injury in elite rugby players. *British Journal of Sports Medicine*, 46(7), 538–542.

de Rome, L., Ivers, R., Fitzharris, M., Du, W., Haworth, N., Heritier, S. & Richardson, D. (2011) Motorcycle protective clothing: Protection from injury or just the weather? *Accident Analysis & Prevention*, 43(6), 1893-1900.

El Mogahzy, Y. (2008) *Engineering textiles: integrating the design and manufacture of textile products*. Cambridge: Woodhead Publishing Limited.

Joo, K. & Kang, T.J. (2008) Numerical Analysis of Energy Absorption Mechanism in Multi-ply Fabric Impacts. *Textile Research Journal*, 78(7), 561-576.

Laing, A.C., Feldman, F., Jalili, M., Tsaic, C.M. & Robinovitch, S.N. (2011) The effects of pad geometry and material properties on the biomechanical effectiveness of 26 commercially available hip protectors. *Journal of Biomechanics*, 44(15), 2627–2635.

Liu, Y., Hu, H., Long, H. & Zhao, L. (2012) Impact compressive behavior of warp-knitted spacer fabrics for protective applications. *Textile Research Journal*, 82(8), 773-788.

Liu, Y., Au, W.M. & Hu, H. (2014a) Protective properties of warp-knitted spacer fabrics under impact in hemispherical form. Part I: Impact behavior analysis of a typical spacer fabric. *Textile Research Journal*, 84(4), 422-434.

Liu, Y., Hu, H. & Au, W.M. (2014b) Protective properties of warp-knitted spacer fabrics under impact in hemispherical form. Part II: effects of structural parameters and lamination. *Textile Research Journal*, 84(3), 312-322.

Nayak, R., Kanesalingam, S., Vijayan, A., Wang, L., Padhye, R. & Arnold, L. (2017) Design of 3D Knitted Structures for Impact Absorption in Sportswear. *The International Conference on Design and Technology*, KEG, 127–134 | DOI: 10.18502/keg.v2i2.605

Ng, J.L., Knothe, L.E., Whan, R.M., Knothe, U. & Knothe Tate, M.L. (2017) Scale-up of nature's tissue weaving algorithms to engineer advanced functional materials. *Scientific Reports* 7, Article number: 40396.

Qin, Z. & Buehler, M.J. (2013) Impact tolerance in mussel thread networks by heterogeneous material distribution. *Nature Communications,* **4**, Article number: 2187.

National Institute of Justice (2000) *Ballistic Resistance of Personal Body Armor*, NIJ Standard–0101.04.

National Research Council (2012) *Testing of Body Armor Materials: Phase III*. Washington D.C.: National Academies Press.

Pain, M.G., Tsui, F., and Cove, S. (2008) In vivo determination of the effect of shoulder pads on tackling forces in rugby. *Journal of Sports Sciences*,26(8), 855-862.

Parker, M.J., Gillespie, W.J. & Gillespie, L.D. (2006) Effectiveness of hip protectors for preventing hip fractures in elderly people: systematic review. *BMJ*, 332, 571.

Schwanitz, S., Möser, S. & Odenwald, S. (2010). Comparison of test methods to quantify shock attenuating properties of athletic footwear. *Procedia Engineering*, 2(2), 2805-2810.

Tyler, D.J.(ed). (2008). *Carr & Latham's Technology of Clothing Manufacture*, 4th edition, Oxford: Blackwell Publishing.

Tyler, D. & Venkatraman, P.D. (2012) Impact resistant materials and design principles for sportswear, Paper 118, *88th Textile Institute World Conference, Malaysia*, May 15-17th 2012.

Varnsverry, P. (2005) Motorcyclists. In: Scott, R.A. (ed.) *Textiles for protection*. Cambridge: Woodhead Publishing Limited, 714-733.

Wang, Z. & Hu, H. (2014) Auxetic materials and their potential applications in textiles. *Textile Research Journal*, 84(15), 1600-1611.

World Rugby (2017), Laws of the game – Rugby Union. Dublin: World Rugby. Online: http://laws.worldrugby.org/ (with links to "Regulation 12. Provisions Relating to Players' Dress (2015)) accessed 20 August 2017.

Wright, J.R., Burns, M.K., James, E., Sloan M.R.& Evans, K.E. (2012) On the design and characterisation of low-stiffness auxetic yarns and fabrics. *Textile Research Journal*, 82(7), 645-654.

Yang, Y & Chen, X. (2017) Investigation on energy absorption efficiency of each layer in ballistic armour panel for applications in hybrid design. *Composite Structures*, 164, 1–9.

Yao, H., Dao, M., Imholt, T., Huang, J., Wheeler, K., Bonilla, A., Suresh, S. Ortiz, C. (2010) Protection mechanisms of the iron-plated armor of a deep-sea hydrothermal vent gastropod. *Proceedings of the National Academy of Sciences*, **107**(3), 987-992.

Yoon S-H. & Park, S. (2011) A mechanical analysis of woodpecker drumming and its application to shock-absorbing systems. *Bioinspiration & Biomimetics*, 6(1), 016003.

Zhao, T., Long, H., Yang, T. & Liu, Y. (2017) Cushioning properties of weft-knitted spacer fabrics. *Textile Research Journal*, Online April 25, 2017. https://doi.org/10.1177/0040517517705630

Zhou, C., Wang, B., Zhang, F., Xu, K., Han, C., Hu, H., Liu, Y., Wang, P. & Xin, J.H. (2013) Micro-gels for impact protection. *Journal of Applied Polymer Science*, 130: 2345–2351.